Red Hole Gamma-Ray Bursts: A New Gravitational Collapse Paradigm Explains the Peak Energy Distribution And Solves the GRB Energy Crisis

James S. Graber*

*407 Seward Square SE
Washington, DC 20003

Abstract. Gamma-ray bursts (GRBs) are still an enigma. In particular the central engine, the total energy, and the very narrow distribution of peak energies challenge model builders. Motivated by recent theoretical developments (string theory, quantum gravity, critical collapse), which suggest that complete gravitational collapse can occur without singularities or event horizons, we explore how red-hole models (which lack singularities or event horizons) can solve these problems better than black-hole models.

KEY GRB MODEL BUILDING CHALLENGES

Gamma-ray bursts vary rapidly and therefore they must be compact. Because these compact gamma-ray bursts release enormous energy, they must form an intense fireball that is optically thick, pair-producing, and thermalized. But the spectrum is not thermal, and there is no sign of pair-production attenuation at the high end of the observed spectrum [1]. This seeming self-contradiction (the opacity problem) can be solved by having the fireball power a relativistic shell or jet that collides with something (perhaps itself) to produce the observed gamma rays [2]. This fireball/shock model is currently the leading candidate to explain GRBs [3]. It has already overcome several severe model-building challenges. But like almost all other published models, it fails to explain the observed spectroscopy of GRBs, particularly the narrowness of the observed peak energy distribution [4,5]. Furthermore, this model does not explain the high ratio of the energy of the GRB burst itself (caused by internal shocks) to the energy in the afterglow (caused by external shocks in the fireball/shock model) [6]. Nevertheless the predictions of this model for the afterglows themselves are consistent with current observations [3].

Finally, there is the problem of the overall energetics of the GRB. The two leading candidates to produce the initial fireball or fireballs –the so-called central engine– are merging neutron stars and core-collapse supernovae [7,8]. Both these sources

have over 10^{54} ergs of total energy available. This is more than enough energy for even the most energetic GRB, but it is not at all clear how to prevent most of it from falling into the newly created black hole which forms in the standard general relativity versions of these models.

There seems to be an inherent conflict between solving the opacity problem and solving the peak energy distribution problem. The only successful technique available to solve the transparency problem is to invoke highly relativistic bulk motion. In the relativistic frame, the gamma rays are below pair-production threshold and so do not suffer pair-production attenuation. This definitively solves the opacity problem. But unless the Lorentz gamma factor of the bulk motion can be fine-tuned to a very narrow range for all GRBs, the resulting blueshift will not only relocate the peak of the photon energy distribution; it will also substantially widen it, inconsistent with the observed narrow E-peak distribution. Thus one needs to find a way to fine-tune the Lorentz gamma factor or find some other way around this conflict. In the fireball/shock model the gamma factor depends sensitively on the baryon loading, and hence will vary widely. Furthermore, the internal shocks model is dependent on shocks with varying Lorentz gamma factors colliding with each other. So fine-tuning is not a reasonable option for this model.

A generic solution to this problem is provided if the relativistic bulk motion results not from an initial explosion, but rather from the gravitational acceleration of matter falling into a deep potential well. An arbitrarily high Lorentz gamma factor can be attained, but the accompanying blueshift will be exactly cancelled when the matter and radiation are redshifted as they emerge from the potential well. (By that time, the matter and radiation will have separated, so the opacity problem has already been solved).

A black hole can provide the necessary deep potential well. But once matter or radiation is deep in the potential well of a black hole, it is almost impossible for it to escape. Therefore, we will consider an alternative gravitational collapse paradigm in which it is possible to escape from deep within the potential well of a gravitationally collapsed object.

WHY CONSIDER ALTERNATE GRAVITY MODELS?

The problems with constructing a GRB model might be sufficient motivation to consider alternate theories of gravity. However, a stronger motivation comes from the theory of gravitation. Recent theoretical developments in string theory, quantum gravity and critical collapse strongly suggest the possibilities of both gravitational collapse without singularities (and without loss of information) and also gravitational collapse without event horizons [9–14]. If these possibilities are correct, we are forced to consider the phenomenological consequences (such as different models for GRBs and core-collapse supernovae) of alternate paradigms for gravitational collapse in which black holes do not form [15].

RED HOLES– A NEW PARADIGM

Many authors have considered the alternative in which a hard core collapsed object similar to a smaller harder denser neutron star forms in place of a black hole [16]. We here consider the alternative in which no such hard surface forms. Instead the spacetime stretching that forms a black hole in the standard model occurs, but it does not continue to the extent necessary to form an event horizon or a singularity. Instead, spacetime stretches enormously, but not infinitely, and forms a deep wide potential well with a narrow throat. We call this a red hole.

This type of spacetime configuration was previously considered by Harrison, Thorne, Wakano and Wheeler (HTWW) in 1965, but only as a way station in the final collapse to a black hole (not yet then called by that name) [17]. In their version, part of the configuration is inside the event horizon, the collapse continues, and a singularity soon forms.

In the new alternate paradigm we call a red hole, no event horizon forms and no singularity forms. The gravitational collapse does not continue forever, but eventually stops. (Why? Perhaps due to quantum effects or string-theory dualities, but we cannot discuss this adequately here.) As the collapse proceeds, the collapsing matter becomes denser and denser until it reaches a critical point, after which, the distortion of spacetime is so great that the density decreases. This happens because the spacetime is stretching faster than the collapsing material can fall inward. (This decreasing density effect was already noticed by HTWW in their analysis of gravitational collapse in the context of standard general relativity [17]. In general relativity, this expansion of spacetime is mostly hidden behind the event horizon and does not prevent the formation of a singularity in a finite time. This is not the case in several observationally viable alternate theories of gravity [18–20].) This is why we are confident that the center of a red hole resembles a low-density vacuum more than it resembles a high-density neutron star. The decrease in density due to this enormous stretching may also be a factor in halting the gravitational collapse of the red hole before the stretching becomes infinite.

As a result, even though the stretching of spacetime is enormous, it never becomes fast enough to exceed the speed of light and cause an event horizon to form. It stops before it reaches an infinite size or any other form of singularity. (Infinite density and infinite curvature also do not occur.) Nevertheless, it is very hard to escape from a red hole. First, there are trapped orbits inside the red hole for photons as well as massive particles, which allows permanent or nearly permanent trapping of mass and energy. Second, the Shapiro delay in crossing a red hole is very substantial, (in some cases, enormous) [21]. Hence particles that are only crossing the red hole or passing through are in effect temporarily trapped.

In fact most of the matter falling into a red hole will be trapped. However, radiation, and highly relativistic matter that falls directly into the center of the red hole and does not rescatter while inside the red hole, can travel straight through and emerge on the other side. This possibility is essential for our proposed new GRB models.

RED-HOLE MODELS FOR GRBS

In order to describe our new red-hole models for GRBs, which are based on modifying the existing fireball/shock model, we begin by resummarizing that model. In the fireball/shock model, some form of gravitational collapse deposits a large amount of energy in a very small region, (which is called the fireball, and also the central engine). The fireball has so much energy in such a small space that a relativistic expansion must occur. Part or all of this explosive expansion travels through a region with a very small critical number of baryons, which absorb essentially all of the energy and form a relativistic blast wave (either spherical or jetted). Multiple such relativistic shells (travelling in the same direction) are created by the central engine, perhaps by repeated explosions (possibly due to repeated accretion events). The faster relativistic shells overtake the slower relativistic shells and collide with them. The internal shocks convert the energy of the baryons to gamma rays,(by synchroton emission or inverse compton scattering or perhaps by both means). The shells eventually collide with external matter and generate the main afterglow. (Perhaps an early prompt afterglow is the result of a reverse shock) [3].

Basically there are three important sites in this model. First, there is the central engine, or fireball site. (In the standard black-hole interpretation, this is probably near a newly forming black hole, perhaps at the pole of a Kerr black hole) [22]. Second, there is the location of the internal shocks, where the main gamma-ray burst is generated. According to Piran, this is typically 10^{12}-10^{14} centimeters, or 30-3000 light seconds down stream from the central engine [3]. Third, there is the location of the external shock, where the relativistic matter collides with material that was not part of the original explosion, and the long-lasting (days to months), but weak (less total energy than the gamma rays) afterglow is generated. In the standard model, this is far from the central engine.

In our alternate red hole models we will relocate these three sites in or near a red hole instead of near the outside of a black hole.

In the first and most conservative red-hole model, we merely replace the black hole of the standard model with a red hole. The red hole can help the central engine by generating more energy than the corresponding black hole or by focusing the outgoing jet more narrowly, but the rest of the model is essentially the same as the standard one and there is no significant impact on the spectral issues. In other words, this first red-hole model can help solve the energy crisis, but does not help explain the broad spectrum, with its unusual slopes and narrowly distributed peak energy.

In the second – and more interesting – red-hole model, the central engine is located at the infalling bottleneck of the red hole, and the internal shocks that generate the primary gamma-ray burst are located at the outgoing bottleneck of the red hole (which is essentially the same place, but at a later time), and the external shocks and the afterglow still occur far away at the point where the ejecta encounter the interstellar material or some other external matter.

In this model, the great internal expansion of the red hole, along with the great

acceleration of the gravitational infall, help to generate the relativistic jet that will later create the GRB. Then the focusing effects of the emerging bottleneck of the red hole help to create the internal shocks necessary for the final transformation of the energy into gamma rays, and to very substantially increase the efficiency of this process. Furthermore, since the blueshift of the infall should be exactly cancelled by the redshift of the outclimb, the gamma rays seen by the observer will have no net red or blue shift (on average). Therefore the observed peak energy will be the same as the initial peak energy. Even if the internal transit involves enormous and substantially varying Lorentz gamma factors, they will not be observed as a net blueshift. So this model helps solve the narrow peak energy distribution problem, as well as the energy crisis. It can also help solve the spectral wideness and slope problems because of the tolerance for differing Lorentz gamma factors during the transit through the red hole.

REFERENCES

1. Band, D., et al., *ApJ* **413**, 281 (1993).
2. Rees, M. J., and Meszaros, P., *MNRAS* **258**, 41P (1992).
3. Piran, T., *Phys. Rep.* **314**, 575 (1999).
4. Preece, R. D. et al., to appear in *ApJS*(1999); astro-ph 9908119.
5. Brainerd, J. J., et al., *ApJ*, submitted.
6. Paczynski, B., and Rhoads, J.,*ApJL* **418**, L5 (1993).
7. Eichler, D., et al., *Nature* **340**, 126 (1989).
8. Woosley, S. E., *ApJ* **405**, 273 (1993).
9. Strominger, A., and Vafa, C., *Phys. Lett.* **B379**, 99 (1996).
10. Callan, C. G. and Maldacena, J. M., *Nucl. Phys.* **B472**, 591 (1996).
11. Maldacena, J. and Strominger, A., *Phys. Rev.* **D55**, 861 (1997).
12. Shapiro, S. and Teukolsky, S. A., *Phys. Rev. Lett.* **66**, 994 (1991).
13. Choptuik, M. W., *Phys. Rev. Lett.* **70**, 9 (1993).
14. Christodoulou, D., *Ann. Math.* **140**, 607 (1994).
15. Graber, J. S., to appear in *Largest Explosions Since the Big Bang* Ed. Livio, M.; astro-ph 9908113 (1999).
16. Robertson, S. L., *ApJL* **517**, 117 (1999).
17. Harrison, B. K., Thorne, K. S., Wakano, M., and Wheeler, J. A., *Gravitation Theory and Gravitational Collapse*, Chicago: University of Chicago Press, 1965, ch. 8, pp. 69-75.
18. Rosen, N., *Ann. Phys.* **84**, 455 (1974).
19. Yilmaz, H., *Ann. Phys.* **101**, 413 (1976).
20. Itin, Y., *Gen. Rel. Grav.* **31**, 187 (1999).
21. Shapiro, I. I., *Phys. Rev. Lett.* **13**, 789 (1964).
22. Kerr, R. P., *Phys. Rev. Lett.* **11**, 237 (1963).